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RESEARCH MEMORANDUM

DETERMINATION OF LONGITUDINAL HANDLING QUALITIES OF THE D-558-II RESEARCH AIRPLANE AT TRANSONIC AND SUPERSONIC SPEEDS TO A MACH NUMBER OF ABOUT 2.0

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Flight tests were performed with the Douglas D-558-II research airplane to investigate the longitudinal handling qualities and trim characteristics at transonic and supersonic speeds up to a Mach number of about 2.0.

Results of this investigation indicate that the apparent stability parameter $d\delta_e/dC_N$ increases by a factor of about 11, the stick force per g increases by a factor of 22, and the apparent stability parameter di_t/dC_N increases by a factor of nearly 5 as Mach number increases from about 0.6 to 1.9. The greater part of these changes takes place in the transonic speed region between Mach numbers of 0.8 and 1.2. The trim capabilities of the airplane with stabilizer and elevator at 1 g are adequate, but in the transonic range and at the higher supersonic speeds, some trim instability is present. The maneuverability of the airplane is seriously limited at high altitudes throughout the transonic and supersonic speed range.

INTRODUCTION

The National Advisory Committee for Aeronautics is conducting flight research at transonic and supersonic speeds by using research-type aircraft at the High-Speed Flight Station at Edwards Air Force Base, Calif. The D-558-II airplanes were obtained for the NACA by the Navy Department in order to conduct flight research on swept-wing airplanes at high speeds. At the present time two D-558-II airplanes are being used in this program, one powered by a turbojet engine and

a rocket engine and the other powered only by a rocket engine. Both airplanes are launched at an altitude of about 30,000 feet from a Boeing B-29 airplane. The two airplanes are essentially the same with the exception of the power plants.

Previous tests of the D-558-II airplanes have shown some data on the longitudinal handling qualities obtained in elevator and stabilizer maneuvers, (refs. 1 to 6). The present paper consists of results obtained with the all-rocket D-558-II airplane (BuAero No. 37974) primarily at Mach numbers greater than 1.0 during power-off and power-on turns and during level flight, and of results of power-on turns made with the jet- and rocket-powered airplane (BuAero No. 37975) primarily at Mach numbers less than 1.0. Longitudinal handling qualities up to the highest speeds at which maneuvers were made with the D-558-II airplanes are described briefly herein.

The data presented were obtained in flight at altitudes between 20,000 and 70,000 feet. Usually the higher Mach numbers were obtained at the higher altitudes, hence no attempts were made to determine effects of altitude on the handling qualities other than the direct effects of lift coefficient on trim for 1 g flight.

SYMBOLS

C_L	airplane lift coefficient, L/qS
C_N	airplane normal-force coefficient, Wn/qS
F_e	stick force, pull is positive, lb
g	acceleration due to gravity, ft/sec^2
i_t	stabilizer angle, leading edge up is positive, deg
L	airplane lift, lb
M	free-stream Mach number
n	normal acceleration, g units
q	free-stream dynamic pressure, lb/sq ft
S	wing area, sq ft
t	time, sec

W airplane weight, lb

α angle of attack, deg

δ_e elevator angle, trailing edge down is positive, deg

INSTRUMENTATION AND METHODS

Standard NACA recording instruments were installed to measure the following pertinent quantities:

Airspeed and altitude
Elevator and stabilizer positions
Angle of attack
Normal acceleration
Pitching velocity
Elevator stick force

All instruments were synchronized by a common timer.

The angle of attack was measured from a vane mounted on the nose boom 42 inches ahead of the apex of the airplane nose. No corrections were applied for boom bending, pitching velocity, or upwash. These errors are believed to be small, especially at supersonic speeds.

The airspeed-altitude system was calibrated by comparing the static pressure measured in the airplane and the altitude of the airplane measured by radar with the pressure and altitude determined from a radiosonde balloon sent up at the time of each flight. The possible Mach number errors are about ± 0.01 at $M = 0.6$ to about ± 0.04 at $M = 2.0$.

The airplane weight and center of gravity during flight were estimated from the known loaded and empty characteristics, the propellant tank geometry, and the estimated propellant consumption.

DESCRIPTION OF THE AIRPLANE

A three-view drawing of the all-rocket airplane used in the present investigation is shown in figure 1. Figures 2 and 3 are photographs of the airplane. Since the two airplanes are essentially the same, photographs and drawings of only the all-rocket airplane are presented. Table I presents pertinent airplane physical characteristics. The

D-558-II airplanes have sweptback wing and tail surfaces and are equipped with an adjustable motor-operated stabilizer controlled by a double-throw spring-loaded switch on the control column. No aerodynamic balance or control boost is used in the control system, although hydraulic dampers are linked to the surfaces to minimize possible control surface "buzz." Figure 4 shows the variation of elevator friction force with elevator angle for slow elevator movement when the airplane is at rest on the ground.

The airplanes were powered by LR8-RM-6 rocket engines which use alcohol-water and liquid oxygen as propellants and have a design thrust of 6,000 pounds at sea level. During some of the flights, nozzle extensions were installed on the rocket engine of the all-rocket airplane in order to expand the exhaust gases to a design altitude of 28,000 feet, thus giving greater thrust at altitudes above 16,000 feet. The jet- and rocket-powered airplane was equipped, in addition to the original rocket engine, with a J-34 turbojet engine having a design thrust of 3,000 pounds at sea level. The turbojet engine exhausts at an angle of 8° below fuselage center line.

Also for some flights the inboard fences shown in figure 1 were not installed on the airplane. Previous tests at transonic speeds (unpublished data) have indicated that the effects of the inboard fences on the longitudinal handling qualities as presented in this paper are negligible, and that they also have little effect in the higher speed range. The data presented are for the clean configuration with slats closed.

TESTS, RESULTS, AND DISCUSSION

Turns and straight-flight runs were made at altitudes between 20,000 and 70,000 feet and at Mach numbers between 0.6 and 2.0. The center-of-gravity location varied from 24 to 27 percent of the mean aerodynamic chord, with most of the data being obtained with the center of gravity at about 25 percent. All wind-tunnel data presented for comparison have been corrected to 25 percent mean aerodynamic chord.

In the left side of figure 5 is shown a time history of the measured quantities of a typical subsonic elevator turn, whereas in the right side angle of attack, elevator, and stabilizer angle are shown as variations with C_N, and stick-force data are plotted against normal acceleration. Figure 6 shows similar plots of a typical turn at supersonic speed. These figures are presented to illustrate in detail the large differences in maneuvering characteristics between maneuvers at subsonic and at supersonic speeds. It may be observed

in figure 5 that when C_N reached moderate values, the relative increase in α and C_N becomes greater than the increase in δ_e, indicating a decrease in the stick-fixed stability and a pitch-up. The values of C_N at which pitch-ups were observed throughout the speed range for the clean airplane are shown in figure 7. This figure was reproduced from reference 7 and corrected with recent data. The subsequent data presented in this paper are confined to the low-lift region well below the pitch-up where the lift, elevator, and stick-force gradients are approximately rectilinear.

Stability Parameters

Figure 8 shows the variation of normal-force-curve slope $dC_N/d\alpha$ with Mach number from Mach numbers of about 0.46 to 1.85, together with wind-tunnel data from references 8 and 9. The wind-tunnel data represent trimmed lift-curve slopes, and, as such, are comparable to the flight data. The value of $dC_N/d\alpha$ increases from about 0.065 at a Mach number of 0.46 to about 0.09 at a Mach number of about 0.86, and thereafter decreases to a value of about 0.05 at a Mach number of 1.85. It appears that there is fair agreement between flight and wind-tunnel data throughout most of the speed range, although the wind-tunnel data give consistently lower results.

The variation of $d\delta_e/dC_N$ for the D-558-II airplane through the range of Mach number is shown in figure 9. This parameter is an indication to a pilot of the over-all steady maneuvering stick-fixed stability. Figure 9 shows that there is a gradual increase in $d\delta_e/dC_N$ up to a Mach number of about 0.8 and a rapid increase with Mach number thereafter to a value of about -85 at $M \approx 1.3$. Above a Mach number of 1.3, $d\delta_e/dC_N$ increases with Mach number at a much slower rate to a value of about -100 at $M \approx 1.9$. The wind-tunnel data of references 8 and 9 show the same general trends in $d\delta_e/dC_N$ as the flight data except at the highest Mach numbers where the wind-tunnel data show values of $d\delta_e/dC_N$ about 30 percent higher at a Mach number of about 1.9.

The variation of dF_e/dn throughout the range of Mach number is shown in figure 10. The stick-force gradient dF_e/dn is an indication of the over-all steady maneuvering stick-free stability of the airplane. As with $d\delta_e/dC_N$, the stick-force gradient dF_e/dn increases slightly to a value of about 20 at $M \approx 0.85$. Above $M \approx 0.85$ the stick-force gradient increases rapidly reaching a value of about 200 at $M = 1.10$; thereafter increasing at a much slower rate up to a value of about 225 at a Mach number of about 1.6.

The variation of di_t/dC_N for the D-558-II airplane through the range of Mach number is shown in figure 11. There is a large increase in di_t/dC_N up to a value of about -11 at $M \approx 1.2$; thereafter, with increasing Mach number, di_t/dC_N increases at an ever decreasing rate up to a value of about -19 at a Mach number of about 1.9. The wind-tunnel data of references 8 and 9 show fair agreement except at the highest Mach numbers where the wind-tunnel values of di_t/dC_L are somewhat higher than comparable flight data.

A large part of the increase in $d\delta_e/dC_N$, dF_e/dn, and di_t/dC_N at Mach numbers below 0.85 may be attributed to an increase in stability inasmuch as references 8 to 10 show that elevator and stabilizer effectiveness increases slightly in this speed range. Above $M \approx 0.85$, however, a large decrease in elevator and stabilizer effectiveness is expected as Mach number increases; therefore, the large changes in $d\delta_e/dC_N$, dF_e/dn, and di_t/dC_N above $M \approx 0.85$ may be attributed both to increase in stability and to loss in control effectiveness. The relative elevator-stabilizer effectiveness is shown in figure 12. Although there are large losses in both elevator and stabilizer effectiveness, it is apparent that the losses of elevator effectiveness at transonic and supersonic speeds are much greater than the comparable losses in stabilizer effectiveness.

Trim Characteristics

The variation with Mach number of the elevator angle required for trim at altitudes of 35,000 and 50,000 feet and a gross weight of 13,000 pounds is shown in figure 13. The data were corrected to the lift coefficient required for 1 g flight at 35,000 and 50,000 feet according to the values of $d\delta_e/dC_N$ shown in figure 9. The subsonic part of the curve for $i_t = 1.9^\circ$ was obtained by applying a correction based on $d\delta_e/di_t$ obtained from figure 12. These were included for completeness and to give results comparable to the wind-tunnel data. The trim curves for an altitude of 50,000 feet are terminated at $M = 0.95$ since at this altitude the airplane will pitch up in 1 g flight below this speed. It may be noted that the elevator angle reached in the curve for $i_t = 0^\circ$ at 35,000 feet is greater than the maximum of 15° available.

The wind-tunnel data from references 8 and 9 show fair agreement except in the transonic region and in the higher supersonic region. However, the trends appear to be about the same at all Mach numbers and stabilizer angles for which comparable data are available.

The stabilizer angles required for trim at 35,000 and 50,000 feet at a gross weight of 13,000 pounds are shown in figure 14. These data were obtained in the same manner as the elevator trim data: by correcting the data according to the values of di_t/dC_N to an ideal lift coefficient for 1 g flight. In addition, a correction was made for the elevator angle when this was not zero, according to the relative stabilizer-elevator maneuvering effectiveness from figure 12. At Mach numbers below 1.0, trimmed flight by the use of the stabilizer is difficult because of the high effectiveness and the lack of feel to the pilot. For this reason the data between $M = 0.6$ and 1.0 at 35,000 feet were obtained by interpolation of a number of elevator trim runs at various stabilizer angles; and though the exact values may not be correct, it is believed that the trends shown are essentially true. At 50,000 feet, the airplane will pitch up in 1 g flight at any Mach number below about 0.95.

The agreement between flight and wind-tunnel data of references 8 and 9 appears to be fair for the most part; however, at subsonic speeds the wind-tunnel data show slightly more trim stability than is indicated by the flight data.

Maneuvering Characteristics

In general, the large values of $d\delta_e/dC_N$ and di_t/dC_N at transonic and supersonic speeds cause a serious loss of maneuverability which was somewhat disturbing to the pilots, especially when flying at high altitudes. Indeed, the maneuverability of the airplane with elevator alone is so poor that all turns at supersonic speeds were completed with the use of the stabilizer. This is illustrated in figure 6 where the elevator was able to provide only an increment of about 0.5g for maneuvering. In figure 15 are shown flight envelopes beneath which controlled flight is possible at altitudes of 35,000 and 50,000 feet. The dashed curve represents the pitch-up boundary, and the solid curve represents the maximum load factor that can be obtained when maneuvering from 1 g flight. The maneuvering ability of the airplane is limited by the pitch-up boundary at speeds below $M \approx 1.6$, and by the control maneuvering effectiveness above a Mach number of about 1.6. An extrapolation of the data indicates that only about 2g can be obtained at a Mach number of 2.0 at 60,000 feet. The data of reference 8 indicate that the loss of maneuvering effectiveness in the transonic region is largely due to an increase of stability; but at Mach numbers above 1.3 it appears that the decreasing lift-curve slopes of the horizontal tail and wing are primarily responsible for the increasing stabilizer required for maneuvering. At higher altitudes, the increasing stabilizer required for trim at 1 g further reduces the maneuverability of the airplane at all Mach numbers.

CONCLUSIONS

Results of a longitudinal handling qualities investigation at transonic and supersonic speeds with the D-558-II research airplane indicate the following:

1. The apparent stability parameter $d\delta_e/dC_N$ increases by a factor of 11, the stick force per g increases by a factor of 22, and the apparent stability parameter di_t/dC_N increases by a factor of nearly 5 as Mach number increases from about 0.6 to 1.9. The greater part of these changes takes place in the transonic speed region between Mach numbers of 0.8 and 1.2.

2. The trim characteristics of the airplane with stabilizer and elevator are adequate for 1 g flight at 35,000 and 50,000 feet; however, in the transonic range and at the higher supersonic speeds, some areas of trim instability are present. The airplane cannot be trimmed at Mach numbers below 0.95 at 50,000 feet because of the pitch-up.

3. The maneuverability of the airplane is seriously limited at high altitude throughout the transonic and supersonic speed range.

4. In general, the wind-tunnel data show fair agreement with flight data throughout most of the speed range for which comparable data are available.

High-Speed Flight Station,
National Advisory Committee for Aeronautics,
Edwards, Calif., July 13, 1954.

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TABLE I.- PHYSICAL CHARACTERISTICS OF THE DOUGLAS D-558-II AIRPLANE

Wing:	
Root airfoil section (normal to 0.30 chord of unswept panel)	NACA 63-010
Tip airfoil section (normal to 0.30 chord of unswept panel)	NACA 63_1-012
Total area, sq ft	175.0
Span, ft	25.0
Mean aerodynamic chord, in.	87.301
Root chord (parallel to plane of symmetry), in.	108.51
Extended tip chord (parallel to plane of symmetry), in.	61.18
Taper ratio	0.565
Aspect ratio	3.570
Sweep at 0.30 chord of unswept panel, deg	35.0
Sweep of leading edge, deg	38.8
Incidence at fuselage center line, deg	3.0
Dihedral, deg	-3.0
Geometric twist, deg	0
Total aileron area (rearward of hinge line), sq ft	9.8
Aileron travel (each), deg	±15
Total flap area, sq ft	12.58
Flap travel, deg	50
Horizontal tail:	
Root airfoil section (normal to 0.30 chord of unswept panel)	NACA 63-010
Tip airfoil section (normal to 0.30 chord of unswept panel)	NACA 63-010
Total area, sq ft	39.9
Span, in.	143.6
Mean aerodynamic chord, in.	41.75
Root chord (parallel to plane of symmetry), in.	53.6
Extended tip chord (parallel to plane of symmetry), in.	26.8
Taper ratio	0.50
Aspect ratio	3.59
Sweep at 0.30 chord line of unswept panel, deg	40.0
Dihedral, deg	0
Elevator area, sq ft	9.4
Elevator travel, deg	
Up	25
Down	15
Stabilizer travel, deg	
Leading edge up	4
Leading edge down	5
Vertical tail:	
Airfoil section (normal to 0.30 chord of unswept panel)	NACA 63-010
Effective area, (area above root chord), sq ft	36.6
Height from fuselage reference line, in.	98.0
Root chord (chord 24 in. above fuselage reference line), in.	116.8
Extended tip chord (parallel to fuselage reference line), in.	27.0
Sweep angle at 0.30 chord of unswept panel, deg	49.0
Rudder area (aft hinge line), sq ft	6.15
Rudder travel, deg	±25
Fuselage:	
Length, ft	42.0
Maximum diameter, in.	60.0
Fineness ratio	8.40
Speed-retarder area, sq ft	5.25
Engines:	
Rocket	LR8-RM-6
Turbojet	J-34-WE-40
All-rocket airplane weight, lb:	
Full rocket fuel	16,000
No fuel	9,550
Jet- and rocket-airplane weight, lb:	
Full jet- and rocket-fuel	15,570
Full jet fuel	12,380
No fuel	10,820

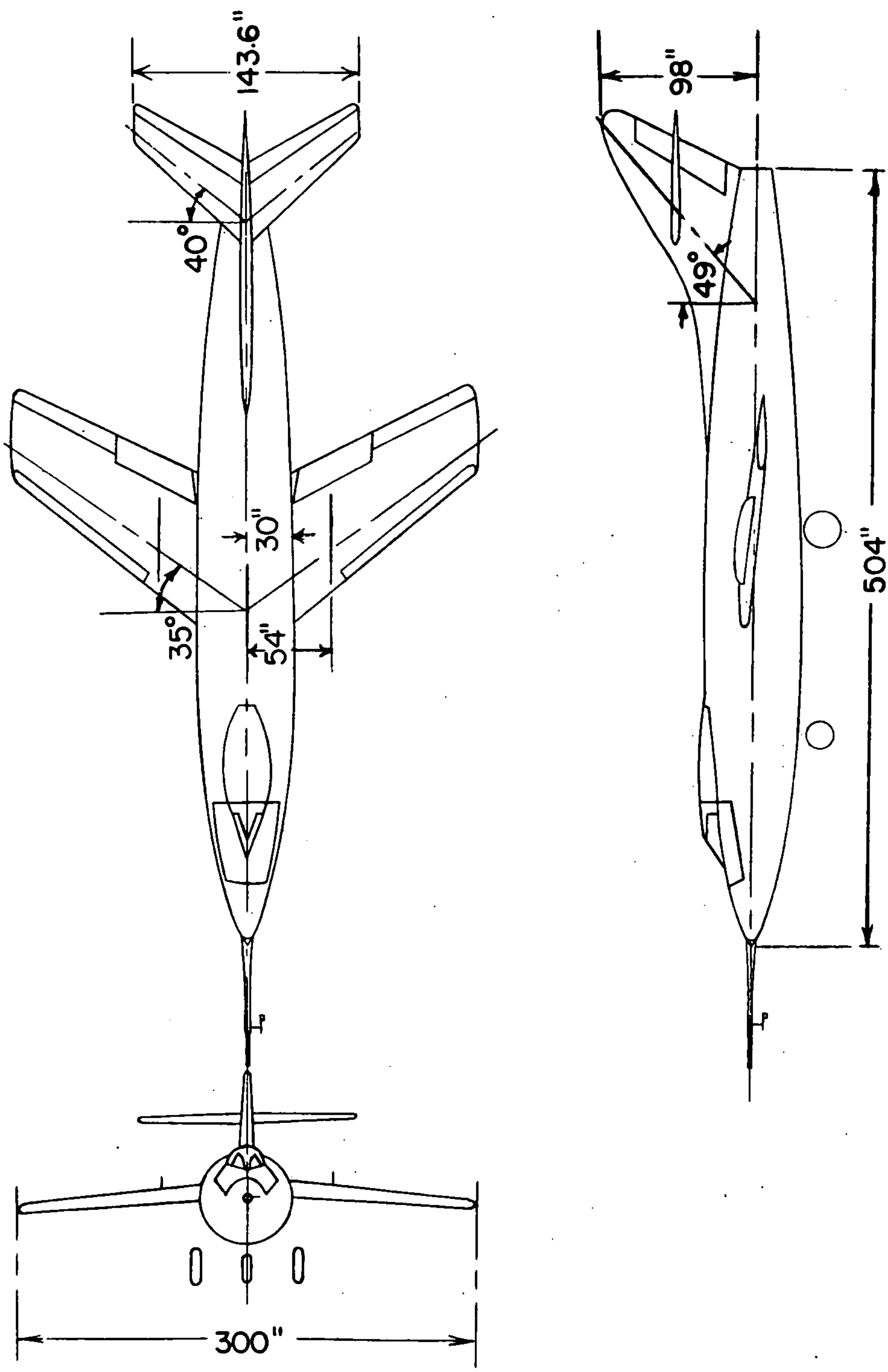

Figure 1.- Three-view drawing of the Douglas D-558-II research airplane. All dimensions are in inches.

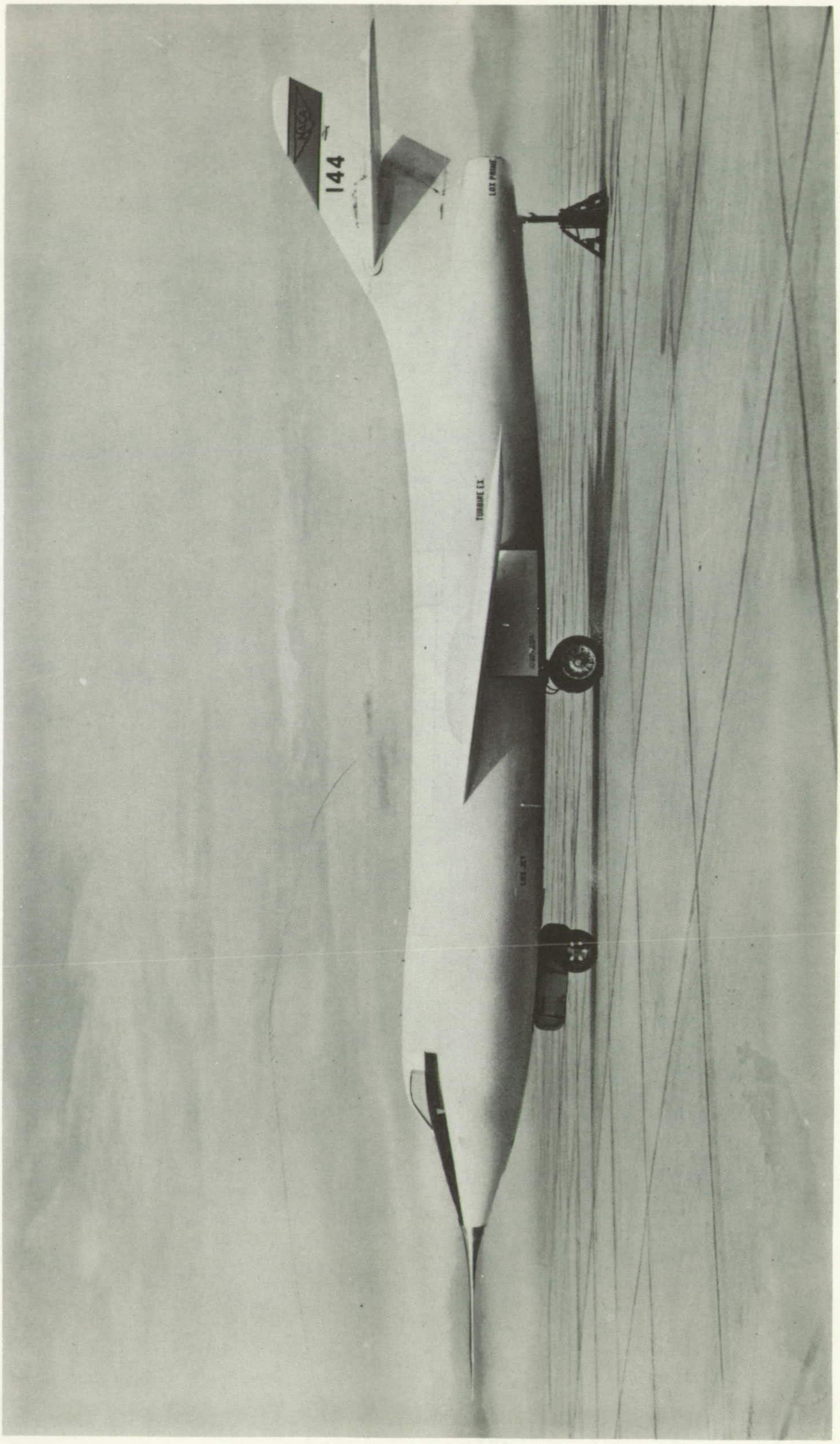

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Figure 2.- Side view of the Douglas D-558-II all-rocket airplane.

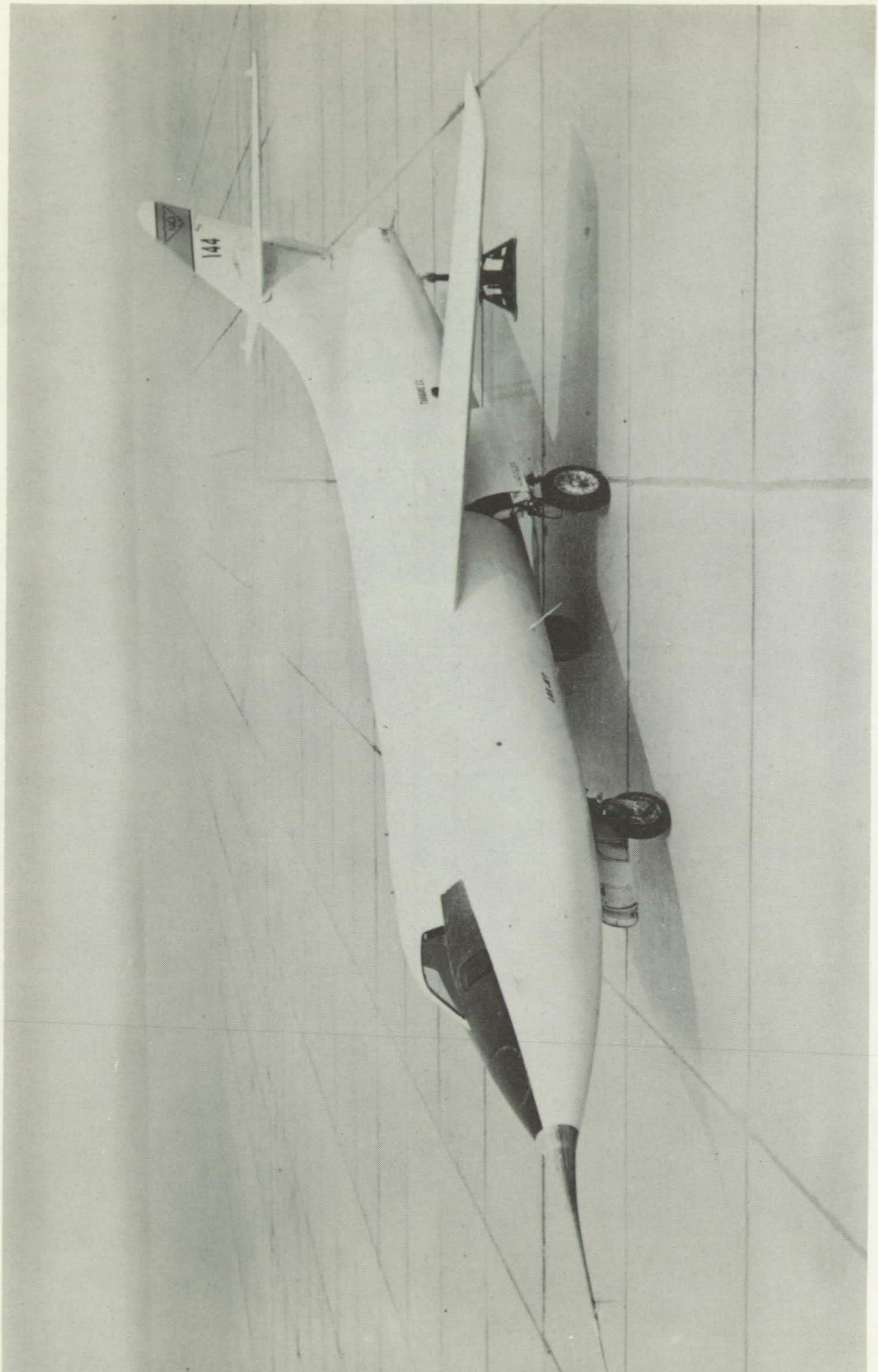

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Figure 3.- Three-quarter front view of the Douglas D-558-II all-rocket airplane.

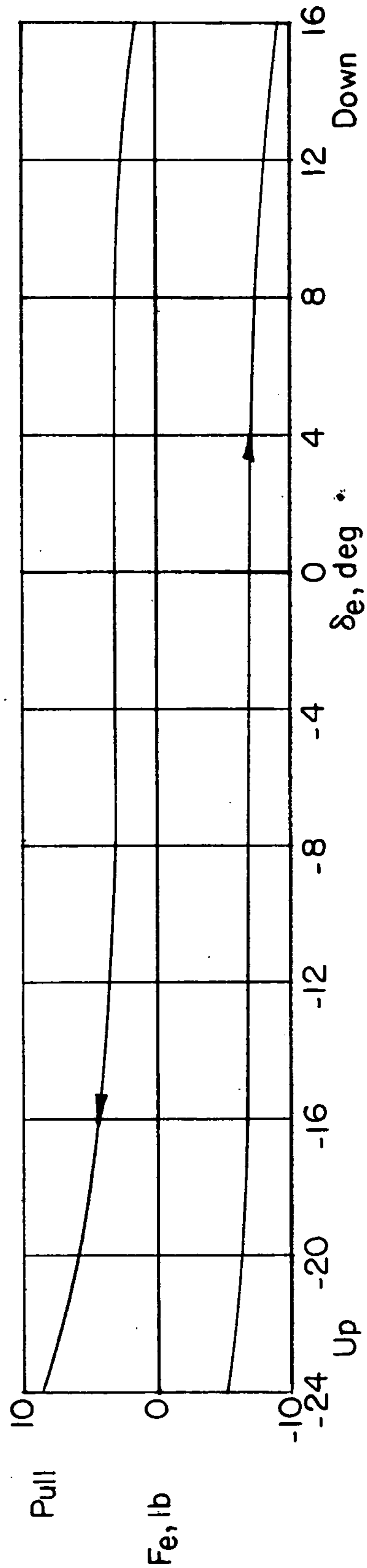

Figure 4.- Variation of elevator control friction force with elevator angle for the D-558-II airplane.

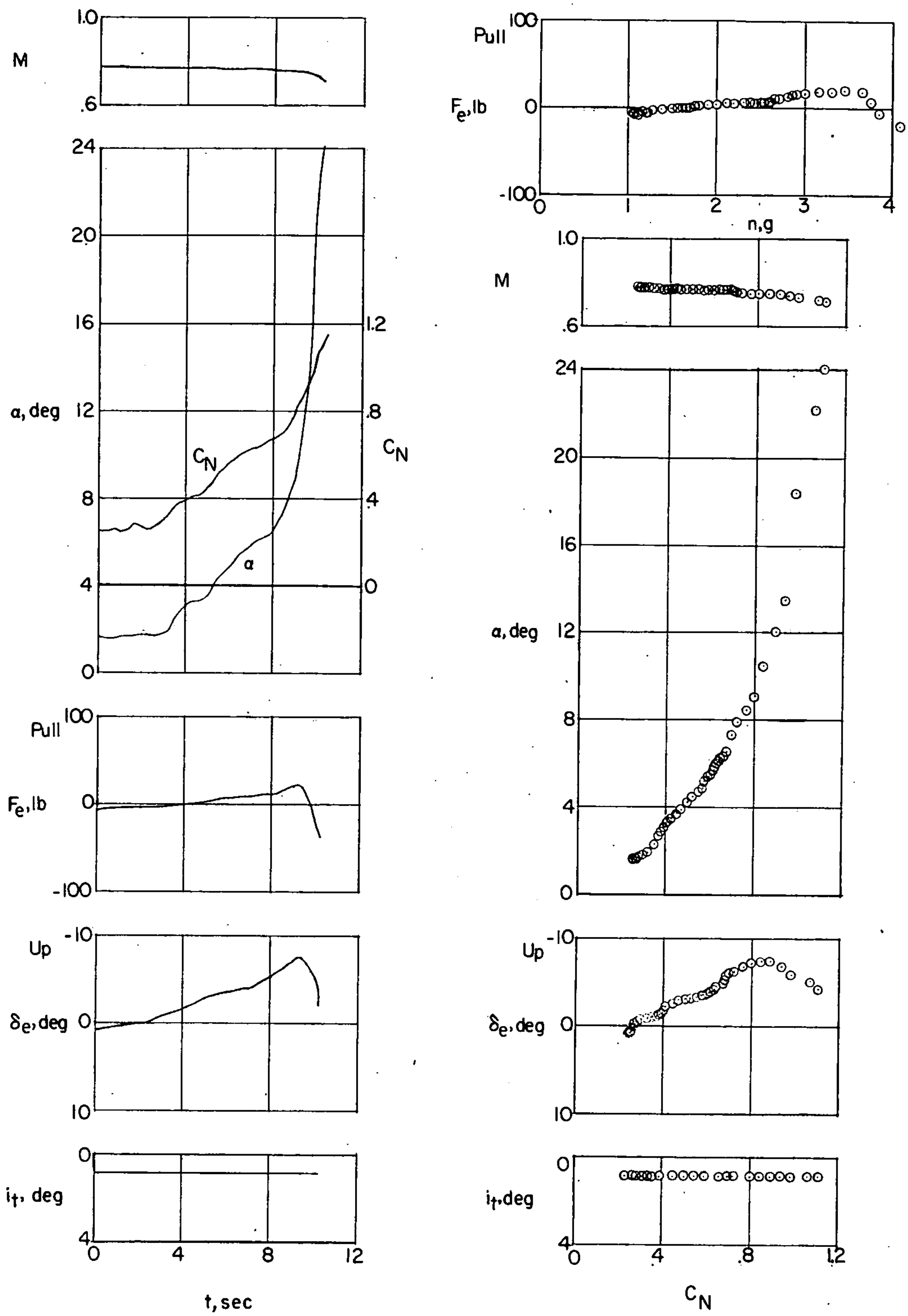

Figure 5.- Variations with time and C_N of data obtained in a typical subsonic turn with the D-558-II research airplane. h_p = 30,000 feet.

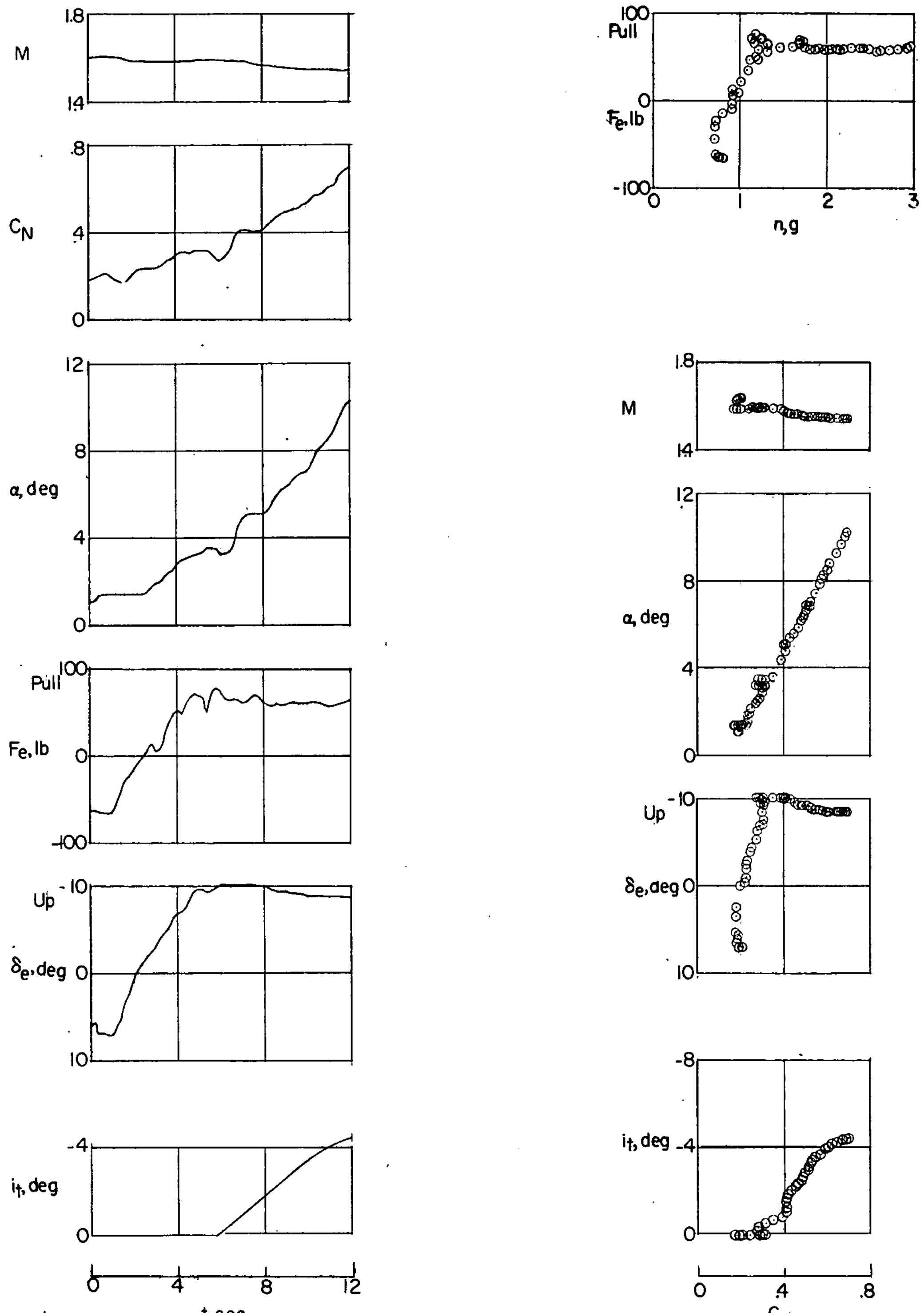

Figure 6.- Variations with time and C_N of data obtained in a typical supersonic turn with the D-558-II research airplane. h_p = 63,000 feet.

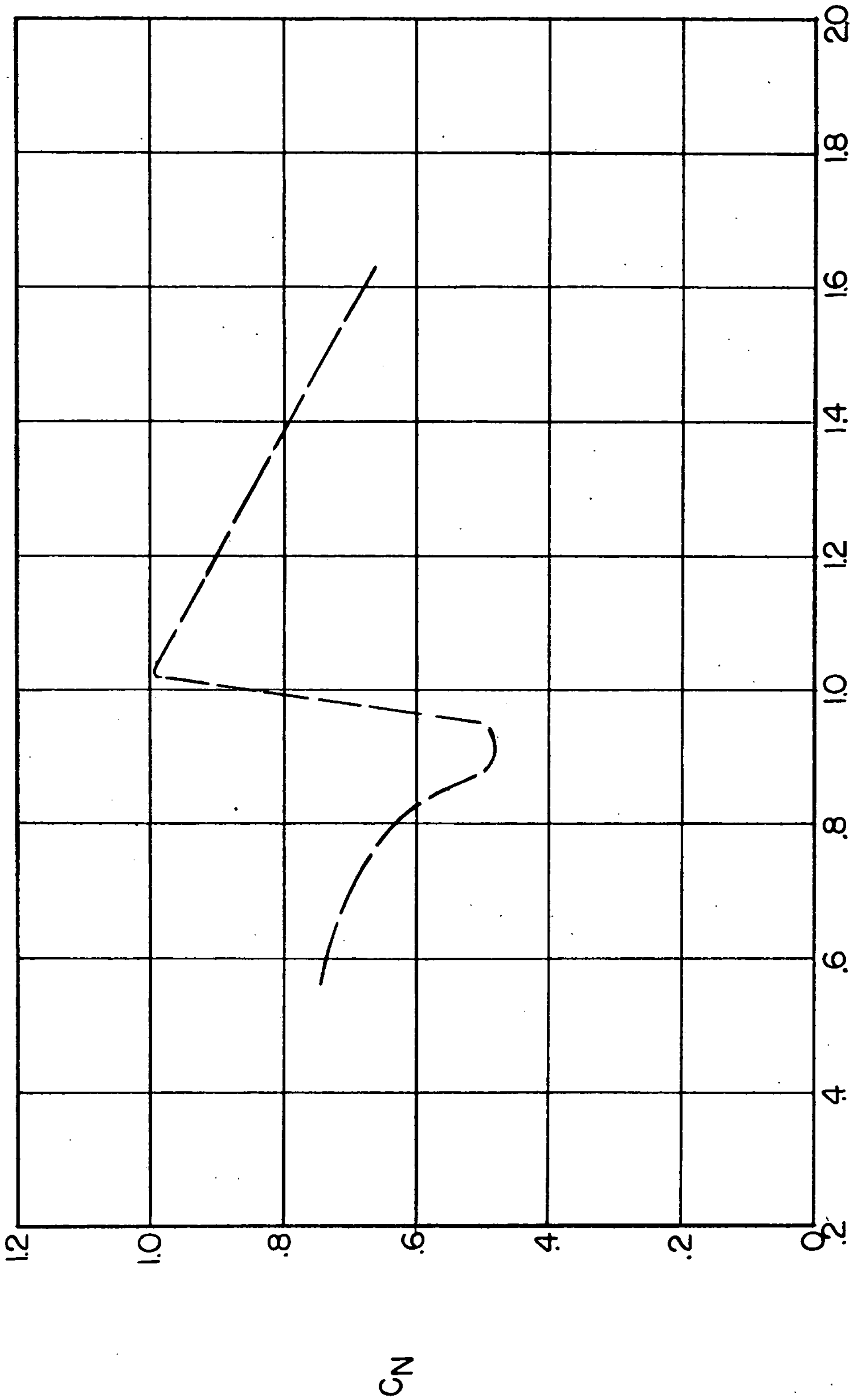

Figure 7.- Variation of normal-force coefficient and Mach number at which pitch-ups occur for the D-558-II airplane.

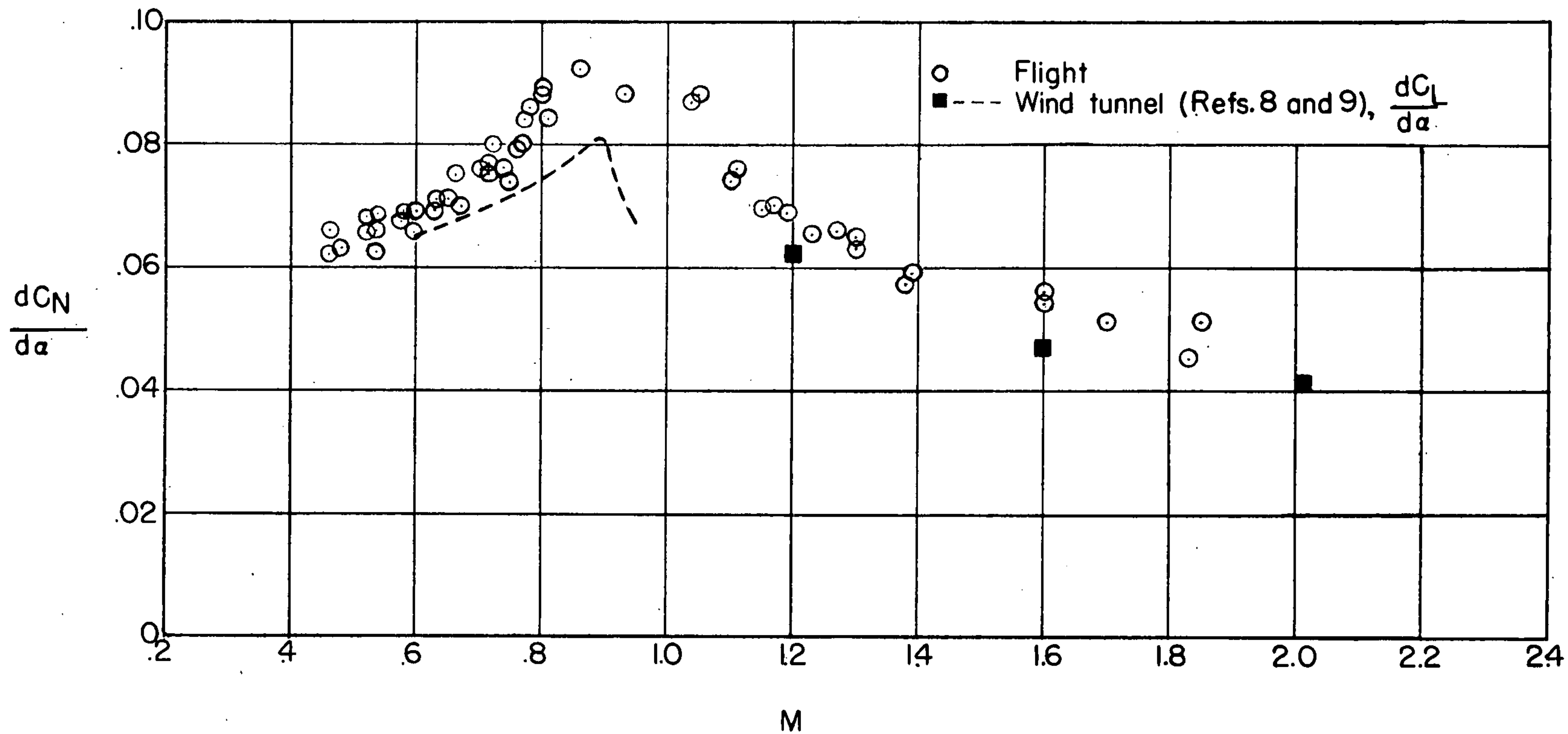

Figure 8.- Comparison of lift-curve slopes as obtained from flight and from wind-tunnel data for the D-558-II airplane.

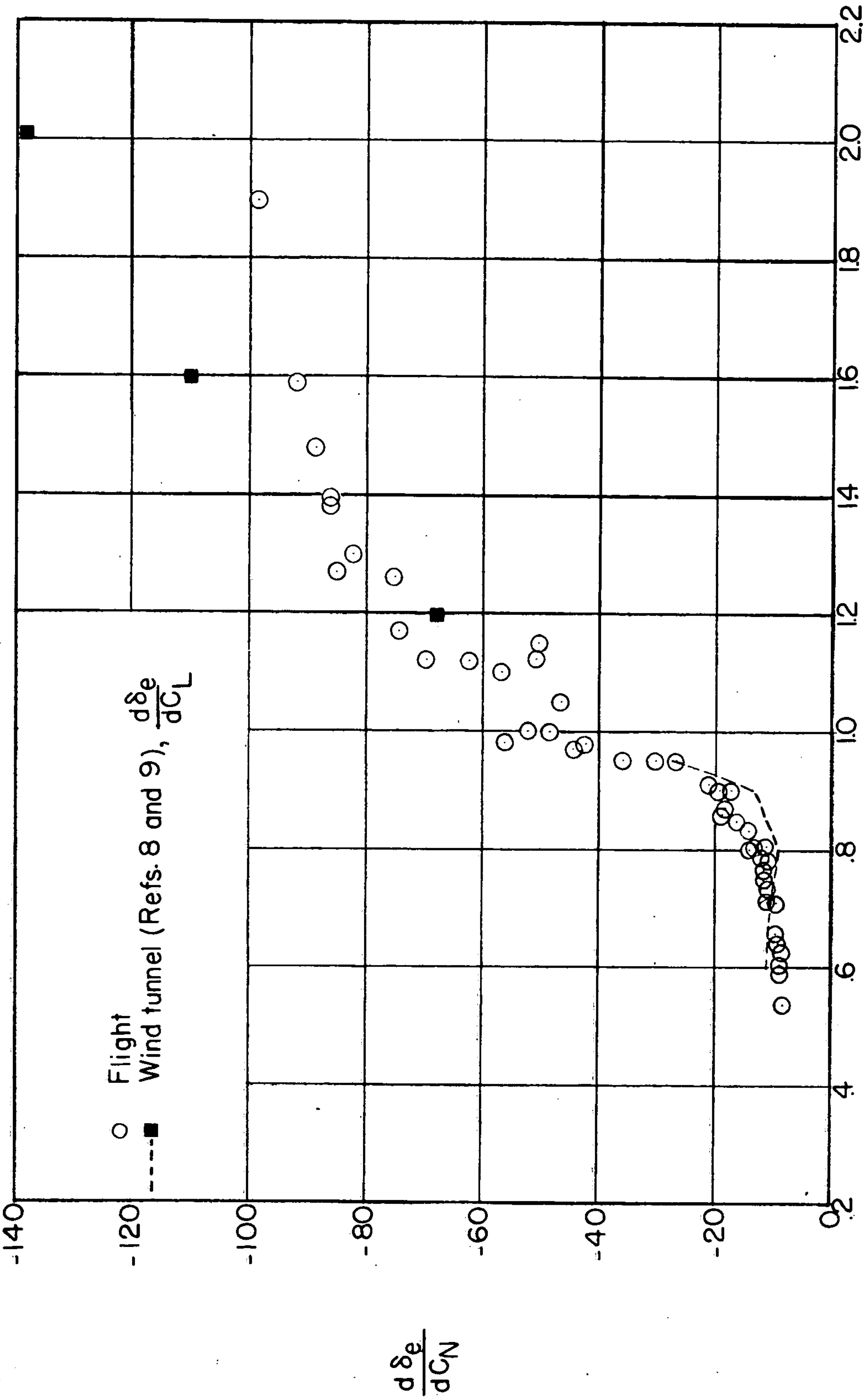

Figure 9.- Variation of $d\delta_e/dC_N$ with Mach number for the D-558-II research airplane.

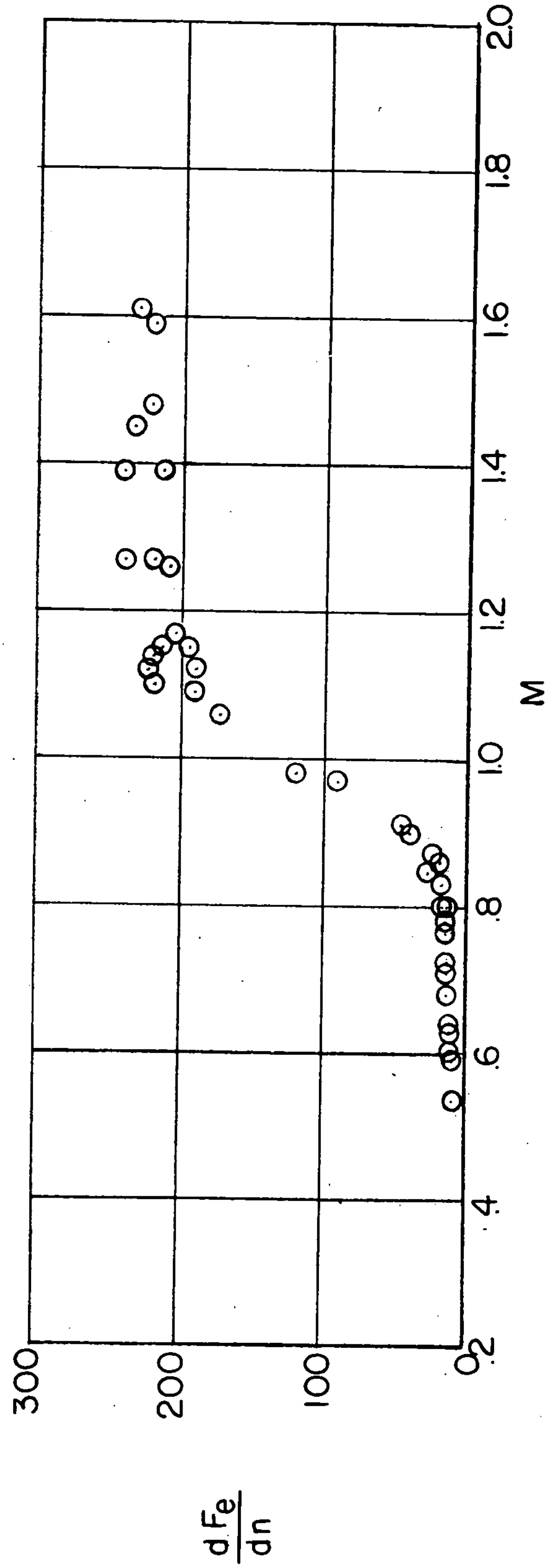

Figure 10.- Variation of stick force gradient with Mach number for the D-558-II airplane.

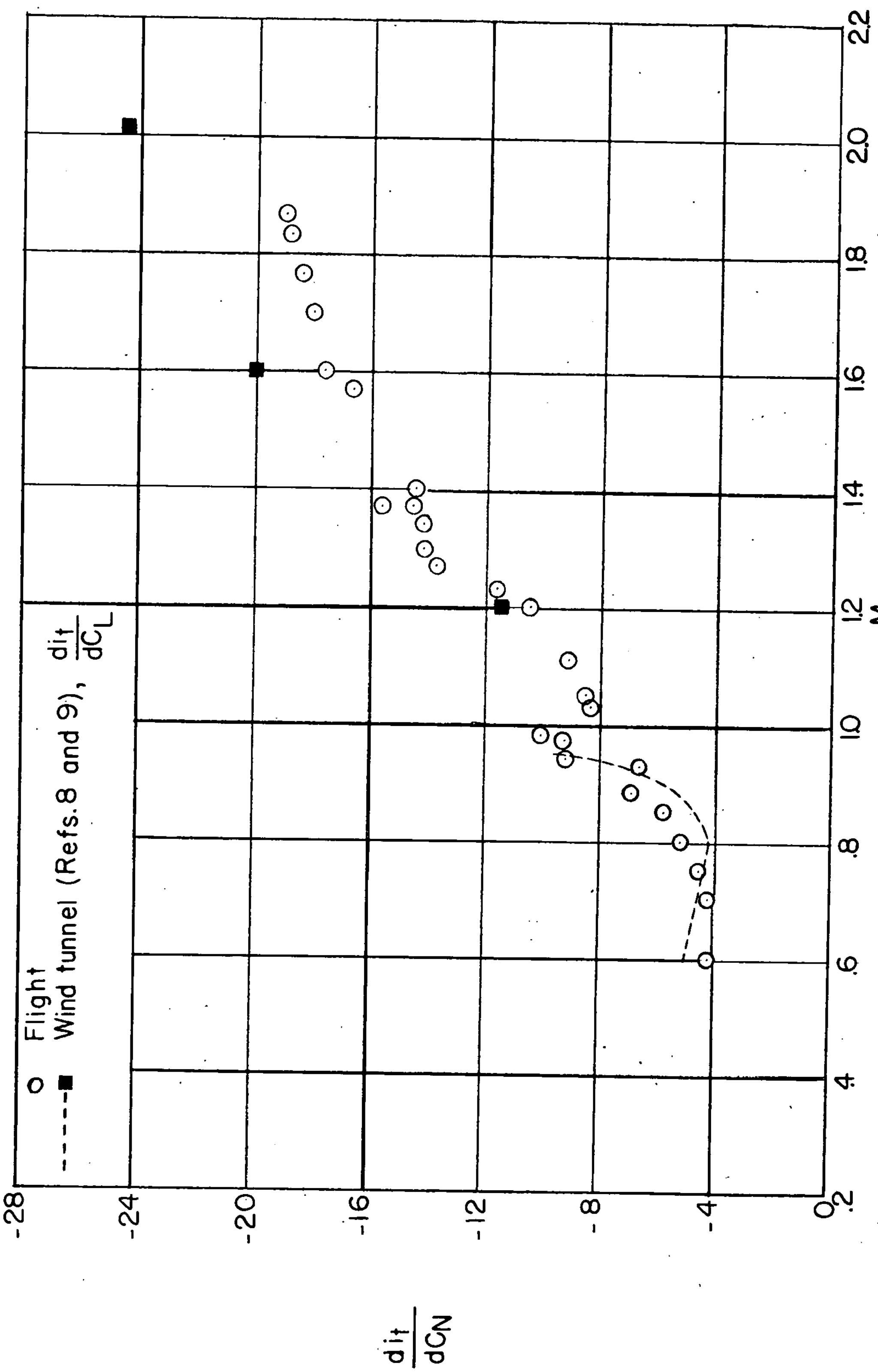

Figure 11.- Variation of di_t/dC_N with Mach number for the D-558-II research airplane.

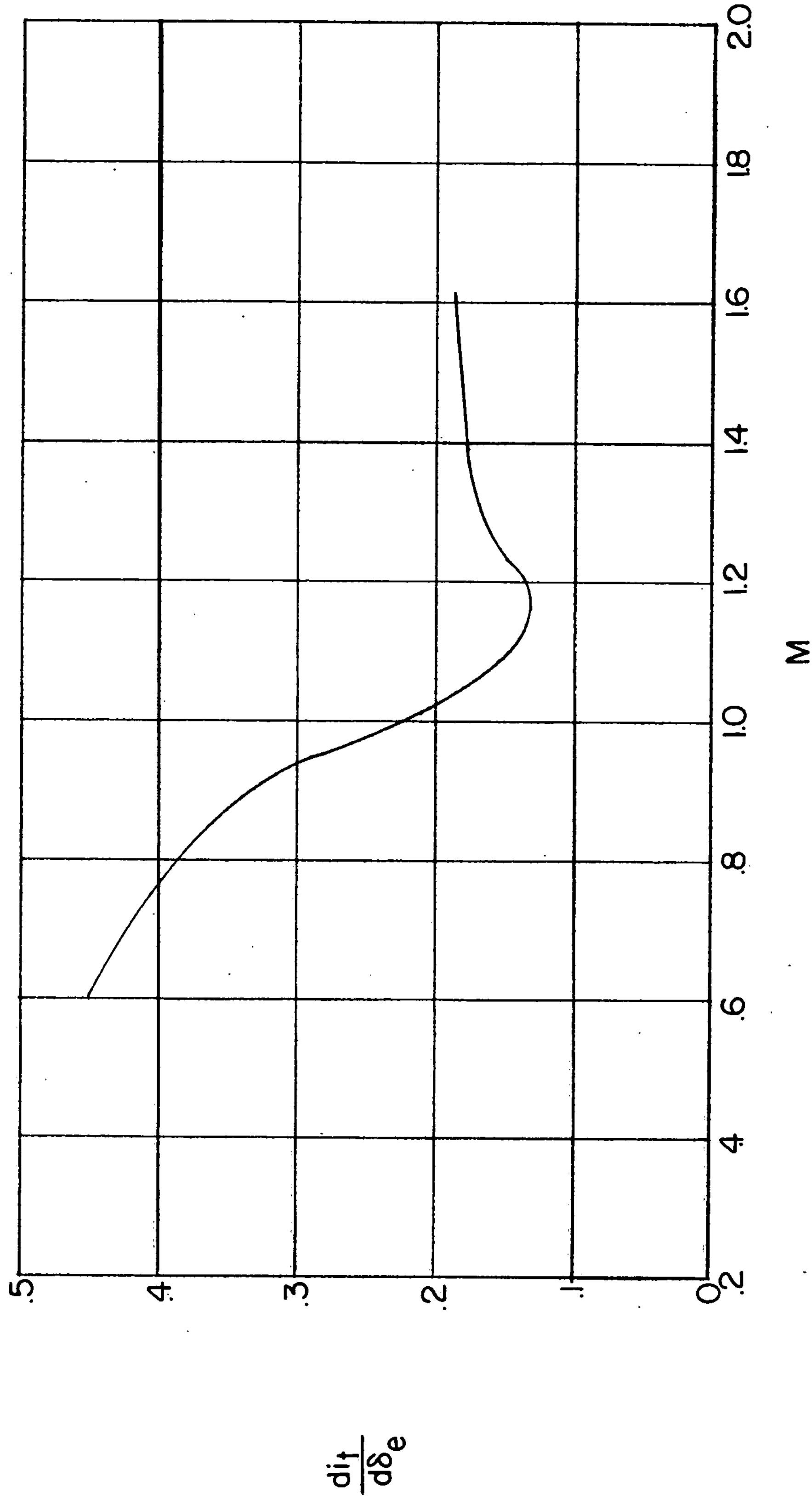

Figure 12.- Relative stabilizer-elevator effectiveness for the D-558-II airplane.

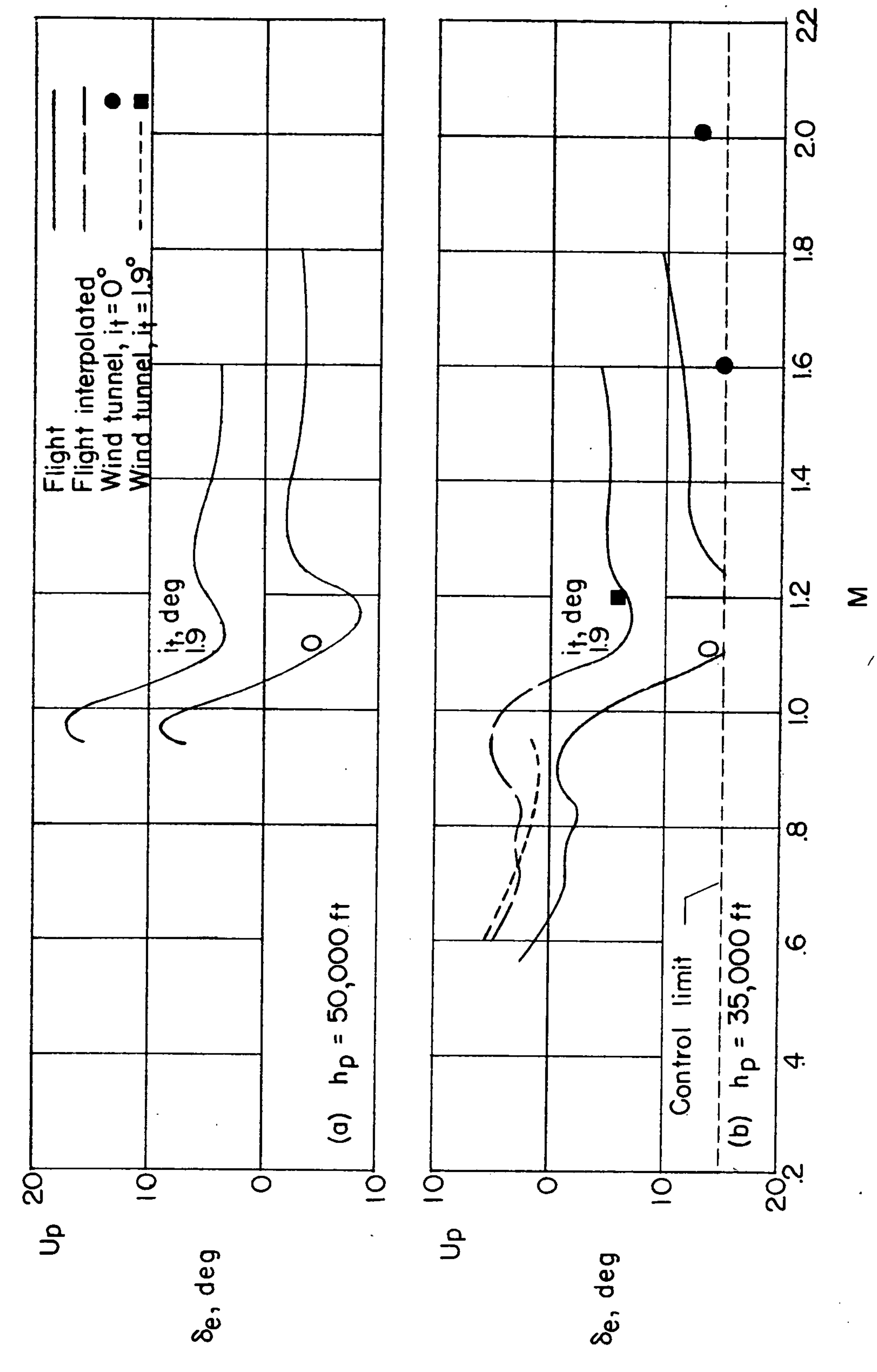

Figure 13.- Variation of elevator angle required for trim through the speed range at altitudes of 35,000 and 50,000 feet.

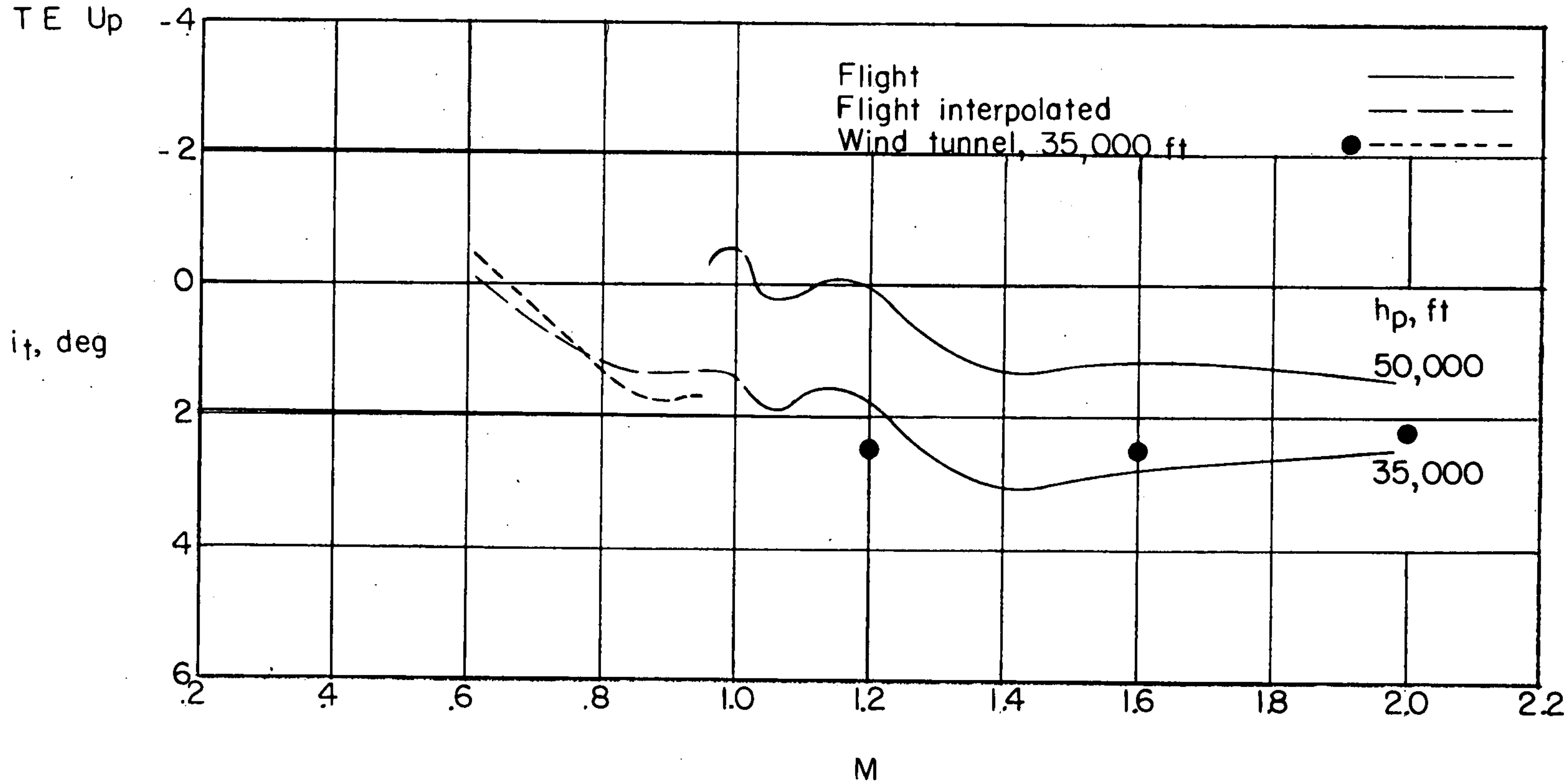

Figure 14.- Variation of stabilizer angle required to trim through the speed range at altitudes of 35,000 and 50,000 feet for the D-558-II airplane. $\delta_e = 0^\circ$.

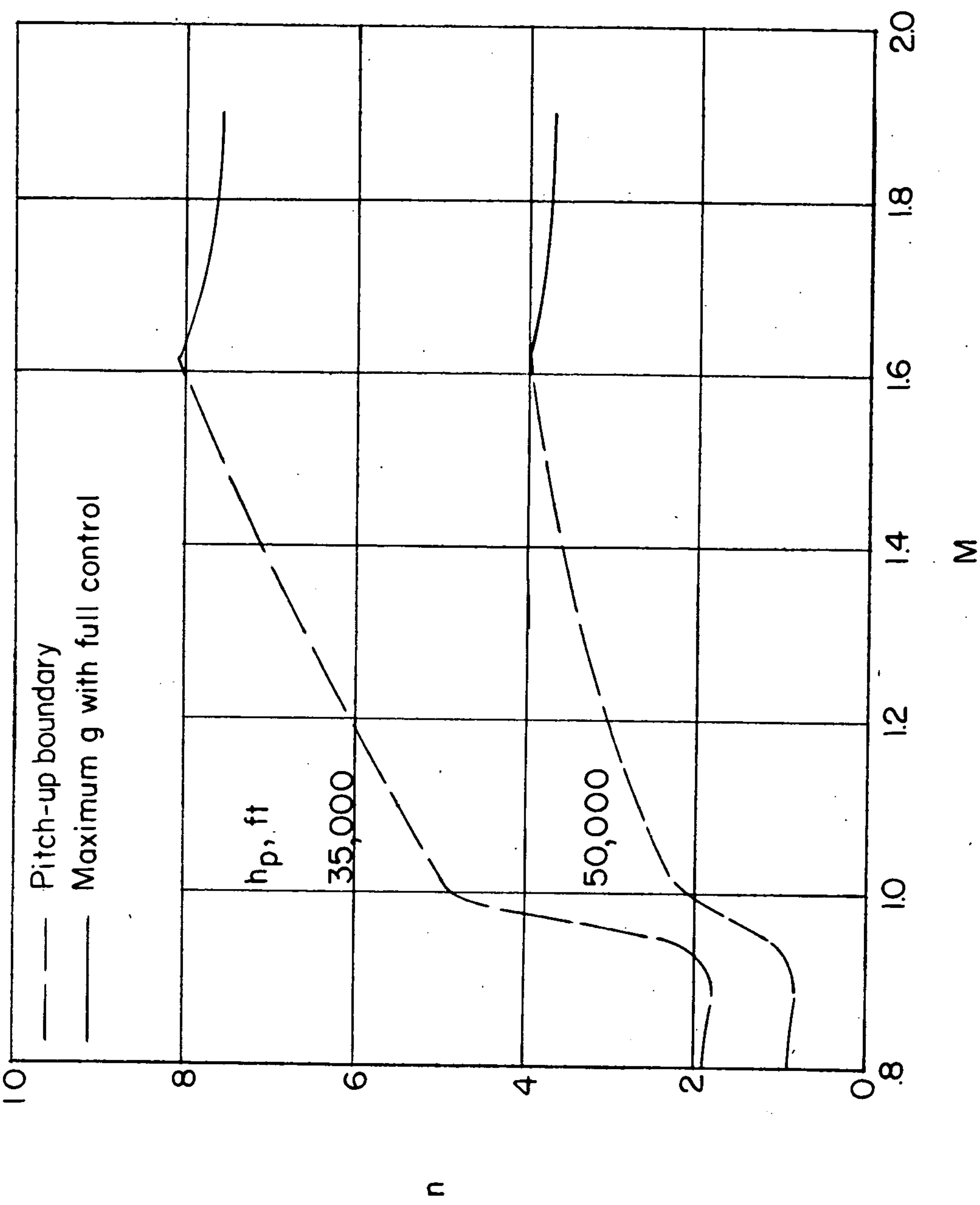

Figure 15.- Envelope of controlled flight region using full stabilizer at 35,000 and 50,000 feet. $\delta_e = -12^{\circ}$.

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